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Observation of t Quark Production at CDF

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ABSTRACT

We present CDF results on the observation of the top quark and the study of its properties using 100 pb^{-1} of data collected at the Tevatron collider at $\sqrt{s} = 1.8$ TeV during the 1992-1995 period. Updated counting results and consistency checks between these data and earlier published mass and cross section are given.

1. Introduction

The top quark is required in the standard model as the weak-isospin partner of the bottom quark. The recent global fit to precision electroweak observables yields a favored mass of $m_{top} = 178 \pm 8^{+17}_{-20} \pm 19$ GeV/c^2 [1].

In April 1994 CDF presented the first direct evidence [2] for $t\bar{t}$ production in $p\bar{p}$ collisions, based on 19.7 pb^{-1} collected at the Tevatron collider at $\sqrt{s} = 1.8 TeV$. An upper limit on the $t\bar{t}$ production cross section was published by the D0 collaboration [3].

In March 1995 both CDF [4] and D0 [5] announced the observation of the top quark, confirming the previous CDF results. Recently, CDF has updated their top results based on approximately 100 pb^{-1} data.

In $p\bar{p}$ collisions, top quarks are expected to be produced in pairs by both gluon-gluon fusion and $q\bar{q}$ annihilation. For a heavy quark mass above 100 GeV/c^2, $q\bar{q}$ annihilation is expected to be the dominant production source. The recent theoretical calculation [6] of $t\bar{t}$ production cross section at the Tevatron gives 4.2 pb for a top mass at 180 GeV/c^2, which is about 9 order of magnitude smaller than the total $p\bar{p}$ collision cross section.

Within the framework of the Standard Model the top quark decays almost exclusively into a real W boson and a b quark for $M_{top} \geq m_W + m_b$. The observed event topology is then determined by the decay modes of the two W bosons. These event topologies are classified into three channels. Decays of W boson to τ lepton are not explicitly included in the search described in this paper except when they subsequently decay to an electron or a muon.

- Dilepton Channel: About 5% of the time both W bosons decay to $e\nu$ or $\mu\nu$, giving two high-P_T leptons with opposite charge, two b jets, and large missing transverse energy ($\not{E}_T$) from the undetected neutrinos. This is the cleanest channel to search for the top.

- Lepton + Jets Channel: In 30% of the cases, one W boson decays to $e\nu$ or $\mu\nu$, and the other to a $q\bar{q}'$ pair. This final state includes a high-P_T charged

lepton, $\not{E}_T$, and jets from the W and the two b quarks. The background comes predominantly from higher-order production of W bosons, where the W recoils against significant jet activity. To suppress the W+multijet background, we apply two different methods for identifying b quarks in the event (btag). The first method uses the CDF Silicon Vertex Detector(SVX) to locate decay vertices of b hadrons as a result of the long b lifetime. The second technique is to search in the event for additional leptons (e or μ) from semileptonic decays of b hadrons (SLT).

- All Hadronic Channels: Finally 44% of the final states involve the hadronic decay of both W bosons, but a huge background from other QCD multijet production processes makes isolation of the $t\bar{t}$ signal extremely difficult. By imposing the SVX btag, kinematic cuts, and reconstructing a top quark mass peak, CDF finally starts to see the top quark signal from this channel.

After the top quark existence has been firmly established, we are going to determine a production cross section from each channel and measure the top quark mass using a subset of the lepton plus jets event. We are also going to examine the kinematic of the $t\bar{t}$ system and compare to the Standard Model expectations. Any surprise could be a link to new physics.

2. CDF Detector

The CDF detector is described in detail elsewhere [7]. The CDF detector consists of a magnetic spectrometer surrounded by calorimeters and muon chambers. The momenta of charged particles are measured in the central tracking chamber (CTC), which is surrounded by a 1.4-T superconducting solenoidal magnet. Outside the CTC, electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, cover the pseudorapidity region $|\eta| < 3.6$, allowing reliable measurements of the missing transverse energy, $\not{E}_T$, which can indicate the presence of undetected energetic neutrinos. The calorimeters are also used to identify jets and electron candidates. Outside the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification. A four-layer Silicon Vertex Detector, located immediately outside the beampipe, provides precise track reconstruction in the plane transverse to the beam, and is used to identify secondary vertices that can be produced by b and c quark decays. A three-level trigger selects the inclusive electron and muon events used in this analysis. To improve the $t\bar{t}$ detection efficiency, triggers based on $\not{E}_T$ were also added.

3. Observation of t Quark from "Counting Experiment"

In the so called "counting experiment" we search for an excess of events over what is expected from known backgrounds. The analysis starts with the high P_T inclusive

lepton sample, which contains an isolated electron with $E_T > 20$ GeV or an isolated muon with $P_T > 20$ GeV/c in the central region ($|\eta| < 1.0$). For the lepton+jets analysis, an inclusive W boson subsample is made by requiring $\not{E}_T > 20$ GeV. The subsample used for the dilepton analysis contains those inclusive lepton events that have a second lepton with $E_T > 20$ GeV. The isolation requirement is looser on the second lepton, and the two leptons must have opposite electric charge. If the ee or $\mu\mu$ invariant mass is between 75 and 105 GeV/c^2, the event is removed as a possible Z boson.

3.1. Dilepton search

The dilepton analysis is very similar to that previously reported [2], except for slight modifications to the lepton identification requirements to make them the same as those used in the single lepton analysis. The dilepton data sample is reduced by additional requirements on $\not{E}_T$ and the number of jets. In order to suppress background from Drell-Yan lepton pairs, which have little or no true $\not{E}_T$, the magnitude of the $\not{E}_T$ is required to be at least 25 GeV. If $\not{E}_T$ is less than 50 GeV, the azimuthal angle between the $\not{E}_T$ vector and the nearest lepton or jet must be greater than 20^0. Finally all events are required to have at least two jets with observed $E_T > 10$ GeV and $|\eta| < 2.0$.

Based on Monte Carlo calculations, we expect 3.6 dilepton candidate events in the $100pb^{-1}$ data for the top quark mass 180 GeV/c^2. The relative acceptance of the three channels(ee,$\mu\mu$ and $e\mu$) are 15%, 28% and 57%, respectively.

The major background are Drell-Yan lepton pairs, $Z \rightarrow \tau\tau$, hadrons misidentified as leptons, WW and $b\bar{b}$ production. We calculate the first three backgrounds from data and the last two backgrounds with Monte Carlo simulation. We find an expected total background of 1.9 ± 0.4 events. We have observed a total of 9 events (1,2,6 in ee, $\mu\mu$ and $e\mu$ channels). Although we have estimated the expected background from radiative Z decay to be small (< 0.1), one of the $\mu\mu$ events contains an energetic photon with a $\mu\mu\gamma$ invariant mass of 86 GeV/c^2. To be conservative, we have removed that event from the final sample, leaving 8 events. The probability of the background to fluctuate to the observed number of events is 10^{-3}. In addition, three of these events contain a total of 5 btags, which provides a strong evidence for WWb. One way in which the events in the $e\mu$ channel can be characterized is shown in Figure 1.

3.2. Lepton + Jets

To search for top events when one of the W bosons decays into leptons and the other W decays into quarks, we start with the standard lepton + jets sample, which requires:
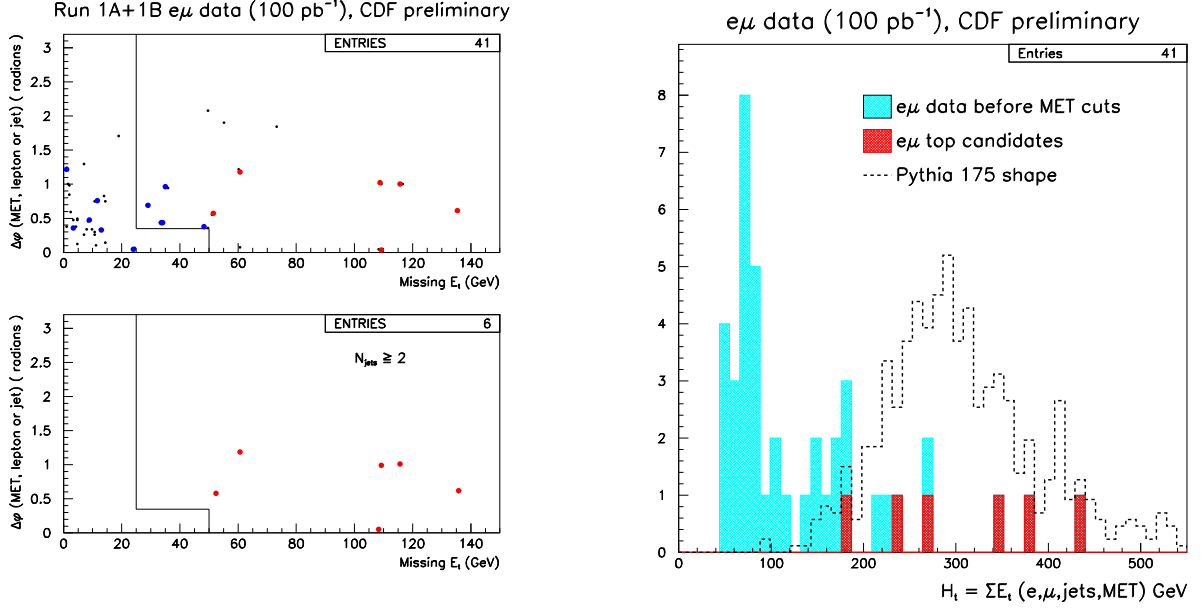
- A primary lepton with $E_T > 20$ GeV

Fig. 1. Left: Distribution of the azimuthal angle between $\not{E}_T$ and the closest lepton or jets in the $e\mu$ sample before and after the two jets cuts. Right: The comparison of total transverse energy distribution between $e\mu$ data and top Monte Carlo, which shows that the characteristic of 6 $e\mu$ candidates events are consistent with top mass 175 GeV/c^2.

- $\not{E}_T > 20$ GeV

- at least 3 jets with $E_T > 15$ GeV with detector $|\eta| < 2.0$

The dominant background in the lepton plus jets search is the continuum of $W+$ multijet production. In $t\bar{t}$ events there are potentially two observed b jets while in W+multijet events only about few % of the jets will contain a heavy-flavor pair from the process of gluon splitting into $b\bar{b}, c\bar{c}$. In order to suppress the background, we attempt to identify b quarks by reconstructing secondary vertices from b decay using the Silicon Vertex Detector (SVX btag) or by finding additional leptons from b semileptonic decay (SLT btag). In 100 pb^{-1} we find a total of 296 W + 3 or more jets. Based on the theoretical $t\bar{t}$ cross section for top mass 180 GeV/c^2, we expect 40 events. CDF currently has two btag algorithms for additional background rejection.

- The primary method consists of a search for secondary vertices from b quark decay(SVX btag). The vertex-finding efficiency is significantly larger now than previously due to an improved vertex-finding algorithm and the performance of a new vertex detector. The new algorithm first searches for vertices with 3 or more tracks with looser track requirements, and if that fails, searches for 2-track vertices using more stringent track and vertex quality criteria. If one is found, we compute the 2-d decay length(L_{xy}), the distance between the primary

and the secondary vertex, and its error. For the criteria of a tag, we require $L_{xy}/\sigma_{xy} > 3$. The efficiency for tagging at least one b quark in the $t\bar{t}$ event with ≥ 3 jets is determined from data and Monte Carlo to be $(42 \pm 5)\%$.

- The second method for tagging b quarks(SLT btag) consists of a search for an additional lepton from semileptonic b decay. Electrons and muons are found by matching CTC tracks with electromagnetic energy clusters or tracks in the muon chambers. To maintain acceptance for leptons coming directly from b decay or from the daughter c quark, the P_T threshold is kept low to 2 GeV/c. The efficiency for finding an additional e or μ in the $t\bar{t}$ events with ≥ 3 jets is $(20 \pm 2)\%$.

The background events are predominantly from the production of W's in association with heavy quarks ($Wb\bar{b}$, $Wc\bar{c}$ and Wc) and mistags due to track mismeasurements. Other much smaller backgrounds include $b\bar{b}$ production, WW or WZ production, Drell-Yan and $Z \rightarrow \tau\tau$. To determine the background we first parametrize the negative decay length tag rate in generic jets data as a function of jet E_T, track multiplicity, and event total transverse energy. We apply this to the W+jets sample to estimate the expected number of mistagged events. For W plus heavy flavor we use HERWIG Monte Carlo samples to calculate the fraction of events expected from various background sources in each of the jet multiplicity bins and their tagging efficiencies. The number of background events is then obtained as the product of these quantities times the observed number of W events in a given jet multiplicity bin. The remaining small physics backgrounds are derived from a combination of data and Monte Carlo. The results are shown in Table 1.

Table 1. Summary of btag jets compared to the expected background for W+jets. The numbers in () are the number of tagged events.

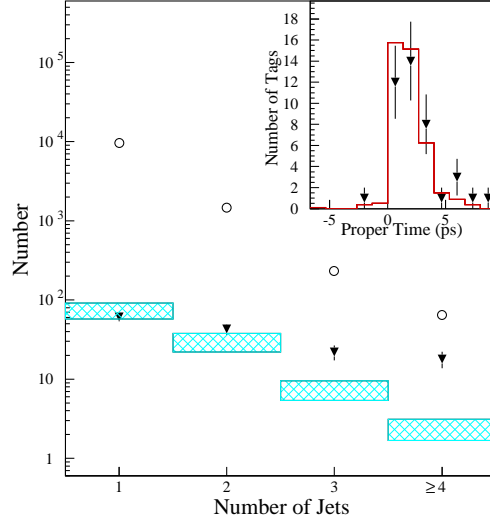| W+Jets	SVX btag		SLT btag	
	Background	Observed	Background	Observed
W+1jet	74.5±16.9	61 (61)	250±38	232(229)
W+2jet	29.7±7.9	43 (38)	71±11	84(83)
W+≥ 3jet	9.9±2.8	40 (32)	23.8±3.6	40(36)

Fig. 2. The number of lepton+jet events(circles) as a function of the number of jets. The number of b-tagged jets(triangles) is compared to the expected background(hatched regions). The inset shows the proper decay time for tagged jets in the W+$\geq$ 3 jets(data points), compared to that expected from b jets in the top events(histogram).

We checked our background calculation using Z+jets events sample, where no top contribution is expected. We observed 6,3 and 1 SVX tags in the Z+1jet, 2jet and $\geq$3jet samples respectively, compared with the background prediction of 8.4, 2.3 and 0.9. With increased statistics, we have directly measured the heavy flavor content by fitting the observed $c\tau$ distribution of SVX tags in the W + jets events, which gives good agreement with our background predictions.

The number of tags in the 1-jet and 2-jet samples are consistent with the expected background plus a small $t\bar{t}$ contribution(Table 1) and Figure 2). However, for the W+$\geq$ 3jet signal region, we find 40 SVX tags with a background prediction of 9.9$\pm$2.8 tags and 40 SLT tags compared to a prediction of 23.8 $\pm$ 3.6. The probability of the background fluctuating to $\geq$ 40 is calculated to be 2. $\times 10^{-6}$ and 6.0 $\times 10^{-3}$ for SVX and SLT tags, respectively. Figure 2 shows the decay lifetime distribution for the SVX tags in the W+$\geq$ 3jet sample, compared to that expected from b decay in top events. We have also studied the kinematic proprieties of these SVX tagged events to make sure they are indeed coming from $t\bar{t}$ events. Figure 3 shows the transverse mass distribution for the lepton plus neutrino and total transverse energy in the tagged events, compared with that expected for 175 GeV top MC. The distributions are in good agreement with top expectation.
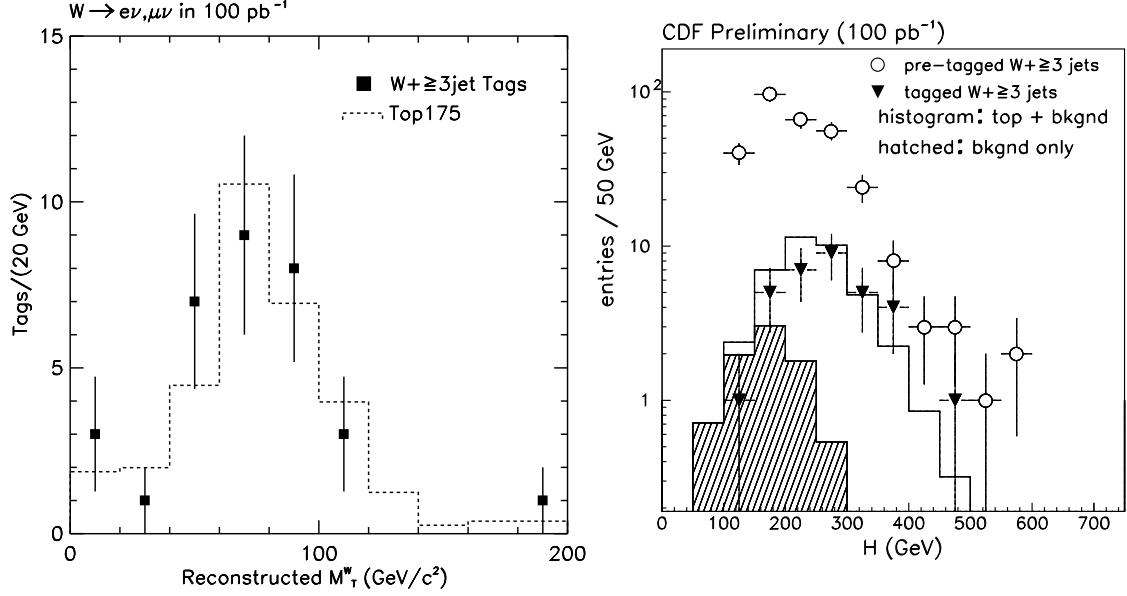
Fig. 3. Left: The transverse mass distribution of the lepton plus $\not{E}_T$ for SVX btag data and top Monte Carlo; Right: The transverse energy distribution for SVX btag data and top MC.

3.3. All Hadronic Decay

As mentioned before, CDF starts to see the top quark signal from the channel in which both W decays into dijets. With two b jets this gives a norminal 6-jet topology. The signal is isolated using a combination of kinematic selection, btag and mass fitting techniques. The data set used for this analysis is based on the 85 pb^{-1} multi-jet trigger sample. In order to suppress the large QCD multi-jet background, we use the following stringent kinematic selections:

- $N_{jet} \geq 6$ ($E_T > 15$ GeV, $|\eta| < 2.0$ and $\Delta R_{min} \geq 0.5$).

- $\Sigma E_T \geq 150$ GeV, $\Sigma E_T / \sqrt{s} \geq 0.75$.

- Require at least one SVX tag present in the event.

- Using 2 vertex fit to $t \rightarrow j_1 j_2 + b$, $\bar{t} \rightarrow J_3 J_4 + \bar{b}$.

- Make all 10 permutation among the 6 leading jets, and choose the best χ^2 solution.

Figure 4 shows the preliminary mass distribution after the kinematic selection. A clear excess above background is seen in the 160-190 GeV/c^2. The number of events
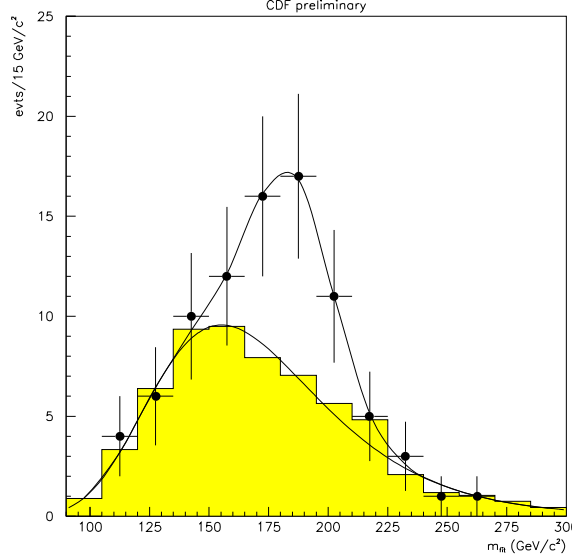
Fig. 4. The CDF reconstructed top mass distribution from the 6 jet sample with at least one SVX btag jet(point). The shaded region is the expected background.

in the peak is 28 ± 10, which correspond to a production cross section of 9.6 ± 3.5 pb. The errors quoted are statistical only. The systematics uncertainties are still under study.

4. $t\bar{t}$ Production Cross Section Measurement

From the excess of events above expected background in the dilepton, SVX and SLT searches using 67 pb^{-1} data, CDF obtains the production section section of: $10.9^{+5.9}_{-4.5}pb$(Dilepton), $6.8^{+2.9}_{-2.3}pb$(SVX), and $6.3^{+5.0}_{-4.1}$(SLT), respectively, where the error is combined statistic and systematics uncertainties. The combined $t\bar{t}$ cross section is $7.6^{+2.4}_{-2.0}pb$.

Figure 5 shows the CDF measured mass and cross section along with the theoretical calculations. It is also consistent with the most recent theoretical calculation by E. Berge and H. Contopanages [8]. We have not yet updated our $t\bar{t}$ cross section with the 100 pb^{-1} data sample , but we have checked that the observed yield is consistent with the measured cross section, as shown in Table 2.

5. Measurement of the Top Mass

The measurement of the top quark mass,together with the CDF measurement of the W mass, provides an important test of the Standard Model. We fit the tagged lepton plus jets events to the $t\bar{t} \rightarrow WbW\bar{b}$ hypothesis using kinematic constrained fitting techniques. Starting with the 296 events with ≥ 3 jets, we require each event
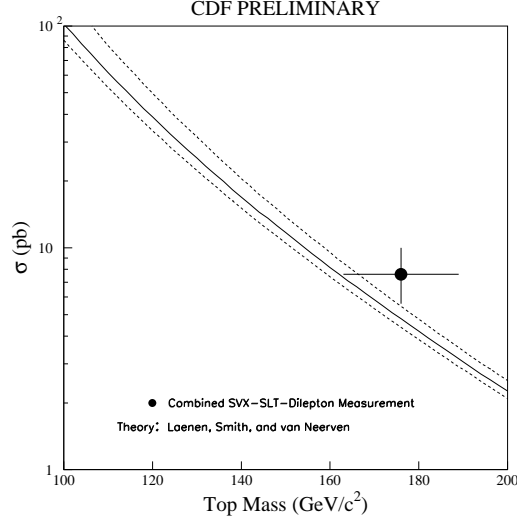
Fig. 5. The measured $t\bar{t}$ production cross section (solid points) compared to the theoretical calculation.

Table 2. The observed number of top candidate events in the 100 pb^{-1}, compared to the expectations based on the measured $t\bar{t}$ cross section in $67pb^{-1}$.

	SVX	SLT	Dilepton
Observed	32	36	9
Expected	34.7 ± 8.1	35.6 ± 4.4	7.8 ± 1.8

to have a fourth jet with $E_T > 8$ GeV and $|\eta| < 2.4$. This yields a sample of 132 events, of which 32 have a btag. The lepton, neutrino and the four highest E_T jets are assumed to be the $t\bar{t}$ daughters and the btag jet is required to be one of the b jets. There are multiple solutions, due to both the quadratic ambiguity in determining the longitudinal momentum of the neutrino and the assignment of jets to the parent W's and b's. For each event, the solution with the lowest fit χ^2 is chosen.

5.1. Studies of Jet E_T Scale

Since we are using observed jets to measure the top mass, the accurate measurement of jet energy is very important for obtaining a precise mass determination. The
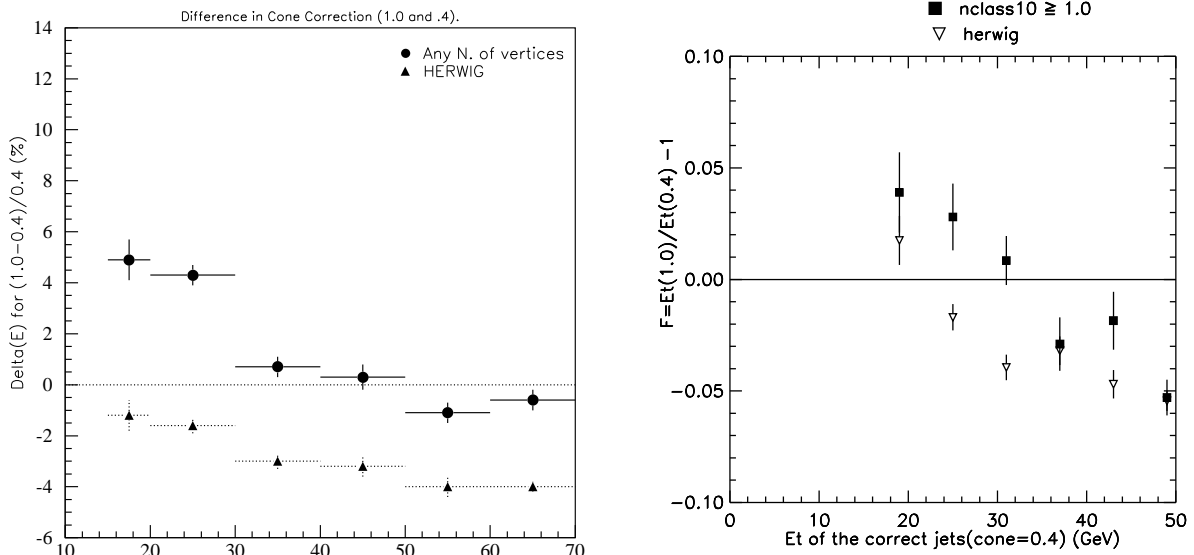
Fig. 6. Fractional difference in the correct E_T in an annulus between cone 0.4 and 1.0 (Left: for generic jets in W+jets; Right: for bjets in $b\bar{b}$).

CDF jet finding employs fixed cone size clustering algorithm and its energy corrections include: detector relative and absolute response, underlying events from multiple interactions and out-of-cone energy correction. The energy scale is checked to be good to 3% by studies of the E_T balance between events with either a Z or γ and a single recoiling jet. Additional understanding of the E_T outside the jet clustering cone comes from examining the E_T in an annular region around a jet in a W/Z sample and b jets in the $b\bar{b}$ sample. If the correction works perfectly, we would expect the difference between the true jet energy obtained after correcting for different cone sizes to be close to zero. We define $F = E_T(1.0)/E_T(0.4) - 1$, where $E_T(1.0)$ and $E_T(0.4)$ are the corrected energies of the jet in cones of 1.0 and 0.4, respectively.

Figure 6 shows the comparison for (a) W+jets and (b) $b\bar{b}$ samples. The agreement between data and Monte Carlo is good to 5 % at lower energy region and 3 % at higher energy region. This is an improvement compared with a 10% uncertainty quoted previously [2]. The resulting systematic error on the top mass is under study.

5.2. Results of Top Mass

The reconstructed mass distribution is shown in Figure 7 for all the events, without requiring that one jet be tagged as a b jet. A clear excess above background is seen in the 160-190 GeV/c^2 region. The distribution is consistent with the predicted mix of approximately 40% $t\bar{t}$ signal with $M_{top} = 175$ GeV/c^2 and 60% W+jets background. After requiring an SVX or SLT btag, 32 of the events remain, of which $8.8^{+2.4}_{-2.2}$ are expected to be background (figure 7). For these events, only the solutions for in which
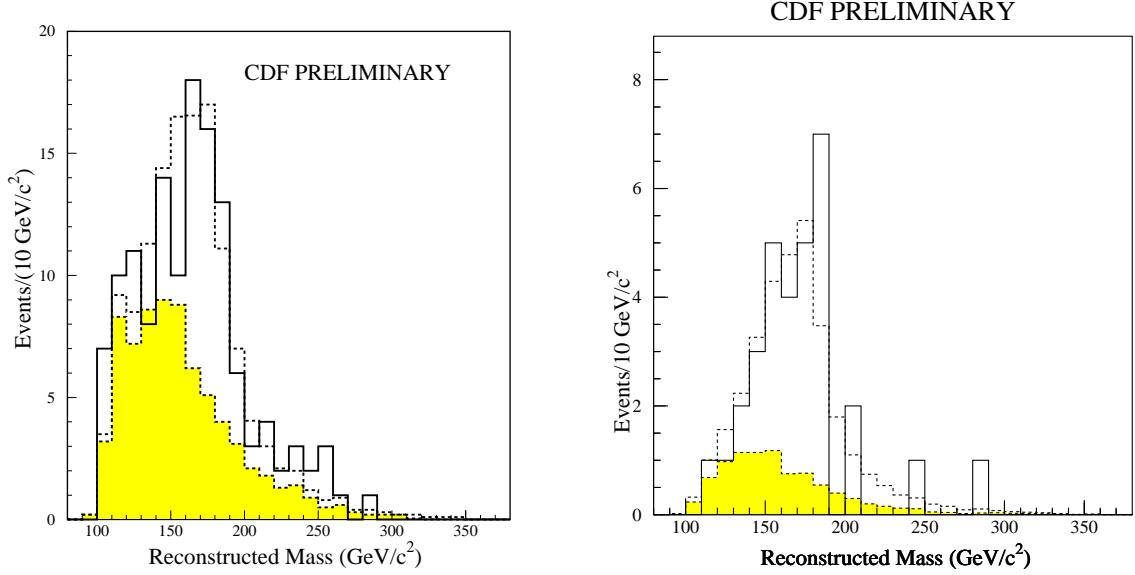
Fig. 7. The reconstructed top-quark mass(histogram) for all the W+ 4jets events without[left plot] or with[right plot] requiring b-tag information, compared to the expected background(shaded) and to the expected background + top signal with $M_{top} = 175$ GeV/c^2 (dashed).

the tagged jet is assigned to one of the b quarks are considered. The distribution is consistent with the published result [4] of $M_{top} = 176 \pm 8(stat) \pm 10(sys)$ GeV/c^2. Work is in progress to improve the systematic uncertainty.

5.3. Search for the Hadronic W in W+4jets

As a further check on the jet energy scale, we have looked for evidence of a second W decaying to dijets and measured its mass in the b-tagged W+ 4jets sample using the following three techniques.

1. Plot the invariant mass for all dijet combinations from the four highest E_T jets. It's straightforward, but suffers by large combinatorics background.

2. Remove the $W \to jj$ constraint in the fit and plot the invariant mass for the jet pair assigned to the W decay by the fitter.

3. Plot the invariant mass of two untagged jets in the double b-tagged $W+ \geq 4$ jets. This is a cleanest way to look for second W, but suffers the statistics.

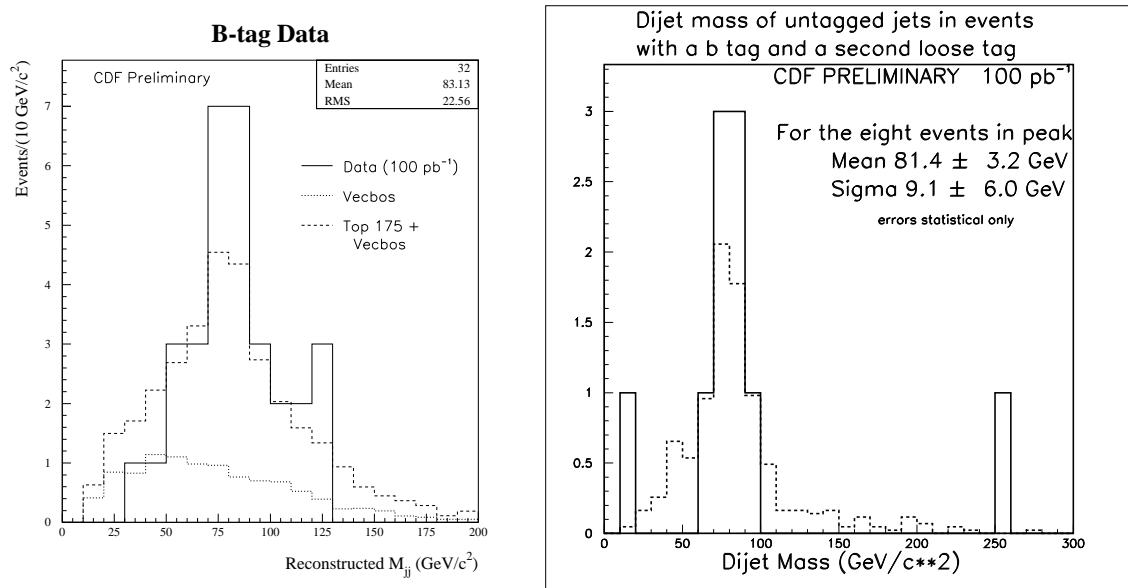Figure 8 shows clear excess over background in the W mass region using method 2. and 3.

Fig. 8. Left: The reconstructed di-jet mass(histogram) for the pair of jets assigned to the W by the mass fitter, compared to the expected background(dotted) and to the expected signal plus background(dashed). Right: The dijet mass of untagged jets in data events with double btag(histogram), compared to the expected signal from top Monte Carlo (dotted).

6. Kinematics of the $t\bar{t}$ System

With the existence of the top quark established, $t\bar{t}$ production properties are of great interest. It is especially interesting to search for non-standard production mechanisms. For example, to search for resonance production of $t\bar{t}$, we looked at both the net transverse momentum and invariant mass of the fitted $t\bar{t}$ pair as shown in Figure 9.

Another way to search for new physics is to measure the top branching ratios($\mathrm{Br}(t \to Wb)$), which is expect to be 100% in the Standard Model. A value significantly different from this could be a signal of new physics. CDF made the first such measurement using the number of top candidate events with one or two jets tagged as b quarks. We found $\frac{Br(t \to Wb)}{Br(t \to Wq)} = 0.94 \pm 0.27(stat.) \pm 0.13(syst.)$. By relaxing the unitarity constraint only on V_{tb} and taking the conservatively allowed values for V_{td} and V_{ts}, we can set $|V_{tb}| > 0.022$ at 95% C.L.

7. Conclusion and Future Prospects

In conclusion, we have shown updated top results with 100 pb^{-1} of data. The results are consistent with our previous publications [4]. The excitement of the discovery
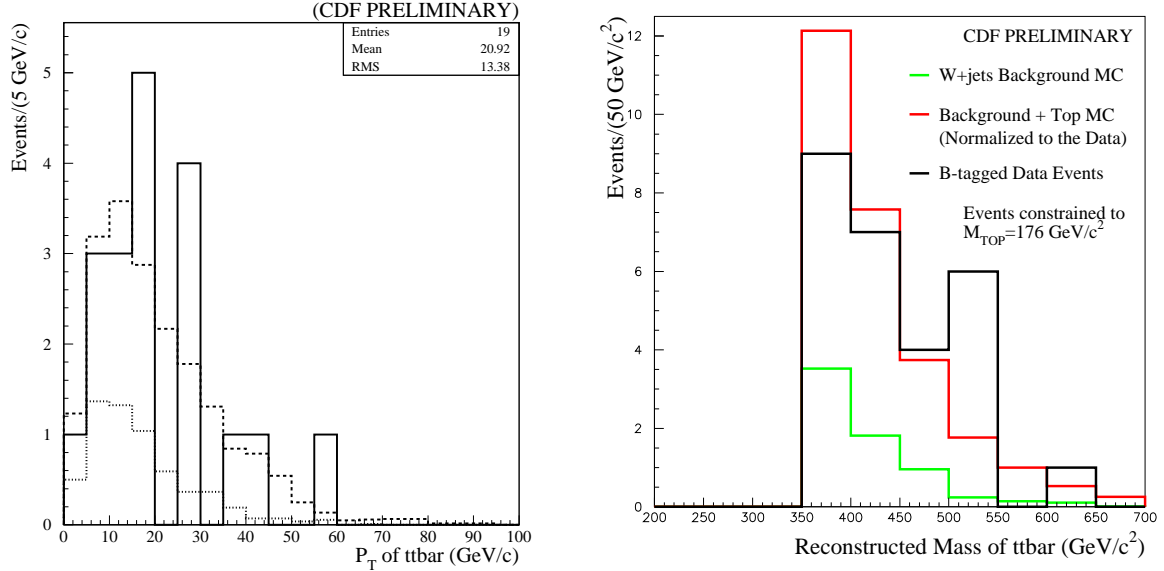
Fig. 9. The reconstructed P_T[left plot] and invariant mass[right plot] of the $t\bar{t}$ system from data(histogran), compared to the background(dotted) and $t\bar{t}$ + background(dashed).

now changes to the exciting possibility that this new heavy state may shed light on some of nature's hidden secrets. In the near future, we expect another 30 pb^{-1} of data for Run1b. We will continue update and improve the top analysis with more data, better understanding of systematic and continue search for new physics. In the long term, the Main Injector and the upgrades to the CDF detector are scheduled to turn on in 1999 with a peak luminosity($10^{32}cm^{-2}s^{-1}$) at $\sqrt{s}$ = 2 TeV. With 2 fb^{-1} of integrated luminosity, we expect more than 1000 single tagged and about 600 double tagged $t\bar{t}$ events. It will allow us to measure the top mass, one of the fundamental electroweak parameters, to approximately 4 GeV/c^2. Measurements of branching ratios, angular distributions and the $t\bar{t}$ production cross section will be performed. In addition, searches for rare decay of the top quark along with searches for exotic physics with the $t\bar{t}$ system will be carried out.

8. Acknowledgements

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